The Dynamics of the Water-Electricity Nexus

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Summary

Electricity has become the basis for our current way of living in modern societies. The electricity we use daily comes from a diverse mix of power plants and power plant types that form a dynamic entity called *electricity grid*, in which power plants interact with each other by scaling production, replacing power plants, or taking turns to fulfill the demand at all times, all year round.

Their installed capacity does define not only the relations among power plants but also other conditions, like changes in the availability of resources required by power plants to produce electricity, e.g., freshwater availability for cooling by thermal power plants, or water for moving turbines by hydropower plants. The use of freshwater by power plants is a critical issue for the expansion of the electricity mix because freshwater is a limited natural resource, which can be subjected to heavy competition between users. This competition will likely intensify in the future as freshwater resources become scarce. The assessment of the water-electricity relationships (known as water-electricity nexus) is paramount.

Freshwater availability, in a specific river basin, often has temporal and spatial dimensions. Water is not available everywhere, and not all the time. This, combined with the dynamic characteristic of the *electricity grid* may create a perfect storm because temporal freshwater availability limitations affect electricity generation so that other technologies elsewhere need to supply production decrease. This might affect their own water resources. Thus, this thesis aims to assess the water use dynamics for electricity generation, considering the spatial and temporal water availability limitations, spatial and temporal effects of constraints on electricity generation systems, and the dynamics in the electricity mix itself. To address this ambitious knowledge gap, I limit its scope using a case study: the Ecuadorian electricity system.

First, in ***Chapter 1*** the *electricity grid* is introduced together with the importance of the water-electricity relationships. It describes the *electricity grid* as a dynamic entity, in which resource fluctuations affect the operation of the power plants in the grid. I show how the *electricity grid* works as a dynamic system in which different conditions (endogenous and exogenous) affect the operation of power plants, creating a cycle where the output from one power plant affects the output of the other. Similarly, the outcomes of one section of this thesis influenced the setting and goals of the others in a meaningful way.

Chapter 2 gives an overview of studies into the water energy relationships and shows that some influential studies that date from the nineties of the 20th century are still cited, often in citation strings, so that the original source is hided. It indicates the lack of data sources of water consumption by power plants, and how the misuse of popular references has introduced bias and uncertainty in case studies, because old data insted of original data were used.

Chapter 3 gives a description of the case study, electricity and water relations in Ecuador. Ecuador is a water-abundant, South American country located at the equator. The Andes mountains split the country in two parts, the Amazon basin in the east and the Pacific basin in the west. Its electricity system is suitable for a case study because: (i) its size is small enough to permit a detailed analysis and still provides global insights as it contains most of the current electricity technologies available; (ii) more than 99% of its demand is fulfilled by the countrys own power plants, electricity exports and imports are negligible. This reduces the uncertainty of the study, as there are no external conditions that need to be considered in the analysis of the electricity system; (iii) the electricity system is located in a heterogeneous geographical setting, with high mountains and flat plains that includes different climates, which permits to assess how different temporal and spatial characteristics affect water-electricity dynamics; (iv) Ecuador is currently undergoing an energy transition, and aims to introduce more hydropower.

Chapter 4 assesses the water footprint of Ecuadorian power plants from a static point-of-view, using first and second-hand data from Ecuadorian sources. It provides the required inventory of power plants and the overall settings for the system boundaries. The chapter quantifies the water use of electricity generation in Ecuador based on annual estimates and the current electricity mix. It provides a baseline for comparison of electricity water footprints of the annual static and the dynamic approach in Ecuador.

Chapter 5 shows the *electricity grid* dynamics, indicating how water availability influences the operation of the power plants in the *electricity grid*. It identifies the importance of hydropower plants (HPPs), in which the *electricity grid* dynamics are shown, including the importance of HPPs in the Ecuadorian *electricity grid*.

Chapter 6, provides a detailed analysis of the Ecuadorian HPPs, showing that the temporal variations of the relationship between electricity output, reservoir size, and climate is paramount to understand the water consumption by power plants. This chapter shows that hydropower water footprints (WFs) can be under or overestimated up until 80% when the temporal variation of reservoir surface size is not considered. It builds upon the previous chapter showing that the temporal variations of the relationship between electricity output, reservoir size, and climate is essential to understand the water consumption by power plants. Similar examples can be seen elsewhere in the thesis.

Together, ***Chapter 5*** and ***Chapter 6*** show how that water availability has large temporal and spatial variations in Ecuador. These variations affect the electricity output of the Ecuadorian power plants inside the *electricity grid*. Although Ecuador is a water rich country, water availability fluctuations affect HPP production, causing reduced electricity production due to water shortages during several months per year. However, when water is limited in the Pacific basin, HPPs in the Amazon basin take over and compensate for lack of production. However, when water is limited available in the Amazon basin, the *electricity grid* is forced to use fossil fueled thermal power plants to fulfil the electricity demand. These changes in electricity output also generate temporal and spatial variations of the WF. When water availability is limited, water-efficient technologies are applied, decreasing the WF of the country. WF changes not only occur due to the temporal production shifts from one type of power plant to the other, but also because HPPs with large storage capacity have significant temporal WF variations due to the relationship between water availability, climate, and electricity planning.

This thesis provides a range of contributions to the existing knowledge on water and electricity relationships, suggesting more sustainable pathways into the future of the water energy nexus of Ecuador. This knowledge can also be applied for countries with similar characteristics and for the water electricity nexus in general.